Student Learning of Complex Earth Systems: A Model to Guide Development of Student Expertise in Problem-Solving

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ABSTRACT

Engaging students in problem-solving concerning environmental issues in near-surface complex Earth systems involves developing student conceptualization of the Earth as a system and applying that scientific knowledge to the problems using practices that model those used by professionals. In this article, we review geoscience education research related to student learning and ill-structured problem-solving in the classroom. This article has two main goals: (1) to propose a model that applies the National Research Council (NRC, 2012) Science and Engineering Practices to students engaged with authentic, ill-structured problems centered on environmental issues and complex near-surface Earth systems (CNSES), and (2) analyze existing literature in the field of ill-structured problem-solving in CNSES to validate the proposed model. Eleven research studies met the inclusion and exclusion criteria. Although none of the selected articles met every component of the model, many of the papers only lacked a few components. We suggest the proposed model will help to alleviate student difficulties in the classroom that arise from lack of background knowledge and enthusiasm about the course or problem, and help guide the design of instructional activities that seek to engage geoscience students in authentic environmental problems. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/17-261.1]

Key words: complex systems, problem-solving, ill-structured problem, expertise

INTRODUCTION

Developing geoscience student expertise in addressing environmental issues associated with complex near surface Earth systems (CNSES) represents an important educational goal, as many students will be working in a field that has some environmental component. Current workforce statistics for geoscientists (which excludes hydrologists) indicate that engineering services and consultants make up 17% and 15% of geoscientists, respectively (U.S. Bureau of Labor Statistics, 2015). If we include hydrologists, it is likely that at least one-third of geoscience students will go on to work in an industry or profession that relates to CNSES. Steiner and Laws (2006) suggest that students should be able to theorize about complex topics, solve simple and complex real-world problems, and use these skills early in their career. Accordingly, students should be able to perform the same tasks in the classroom, especially at higher educational levels (Xun and Land, 2004). In fact, Stuckey et al. (2013) suggest that as educators, we should (1) prepare students for the workforce, (2) expose students to relevant STEM (science, technology, engineering and math) principles that students can use in their lives, and (3) prepare citizens to make decisions about environmental, scientific, or engineering problems. This places pressure on the academic community to prepare students for the practical application of their knowledge to activities like problem-solving and decision-making connected to environmental problems (Steiner and Laws, 2006; Remington-Doucette et al., 2013).

The development of problem-solving skills in real-world situations is not only of interest to geoscientists, but to many other professions and the public in general, especially when addressing environmental issues associated with CNSES such as climate change and flooding (NRC, 2012). These issues should be addressed in the classroom, and identifying a framework can help instructors and researchers to organize teaching practices and design instructional activities. Scherer et al. (2017) identified four distinct frameworks for complex systems within the geoscience education research literature: Earth systems perspective, Earth systems thinking skills, complexity sciences, and authentic complex Earth and environmental systems (see Scherer et al., 2017, for a more detailed explanation). For this work we are operating within the "authentic complex Earth and environmental systems" framework. This framework focuses on "the scientific study of environmental or ecological systems with clear connections to human activities and environmental decision making" (Scherer et al., 2017).

Geoscientists often view the earth from a systems perspective, which provides a frame to understand interactions on the planet in the form of co-dependent systems, such as a watershed or a coastal region. In contrast with a more traditional view of the geosciences, which focuses on individual components or phenomena and is often taught in a way that focuses on facts about science and the Earth that are disjointed and unrelated, the Earth systems approach guides students to a fundamental understanding that everything on the earth is connected, and the Earth system as a whole can be broken down into subsystems with specific characteristics (Ben-Zvi Assaraf and Orion 2005; Raia, 2005; Raia, 2008; Stillings, 2012; Orion and Libarkin, 2014). These types of subsystems, especially when near to the surface, have open boundaries that enable the flow of energy and matter, and so it is difficult to predict the behavior or the dynamics of the system (Herbert, 2006). These same types of systems also typically display behavior

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including nonlinearity, negative and positive feedbacks, and emergent behavior that may not result from interactions with phenomena from outside of a particular system (Peak et al., 2004; Herbert, 2006; Raia, 2008). The properties of these near-surface Earth systems promote a chaotic environment that can be far from equilibrium, and so we can call these systems *complex* near-surface Earth systems (CNSES; Bak et al., 1987; Carlson et al., 1990; Herbert, 2006).

Student Problem-Solving in Complex Earth Systems

CNSES are difficult for students to understand, and Herbert (2006) and Sell et al. (2006) summarize the five common areas of difficulty associated with student learning of CNSES: (1) describing boundaries and interactions of systems including the flow of matter and energy; (2) describing patterns, causal relationships, and emergence over spatio-temporal scales; (3) production or use of models, both mental and external, to anticipate or predict solutions to problems; (4) knowledge transfer from other fields including chemistry, physics, and other disciplines to grasp the complexity of the system; (5) identification of the scale on which the subsystem functions, from nanoscale to global scale, and the impact of the scale on the problem in question. These five barriers are not insignificant, and previous research has addressed many of these problems and tried to assess the state of student systems thinking (e.g. Orion, 2002; Kali et al., 2003; Ben-Zvi Assaraf and Orion 2005; Libarkin et al., 2005; Raia, 2005; Sell et al., 2006; Sibley et al., 2007; McNeal et al., 2008; Raia, 2008; Clark et al., 2009; Miller et al., 2010; Batzri, 2015). This phase of research has been instrumental in the development of teaching strategies, curriculum, and assessments of student thinking and learning about Earth systems; for a more thorough review of this literature we refer you to Ben-Zvi Assaraf and Orion (2005), Stillings (2012), Orion and Libarkin (2014), and Scherer et al. (2017).

A separate yet related subfield of systems thinking has emerged in geoscience education that focuses on how students use knowledge about complex systems to solve problems. Problems, in general, can range from simple, or well-structured, to complex, or ill-structured (Simon and Gilmartin, 1973; Chi et al., 1981; Voss, 1988; Voss and Post, 1988; Sinnott, 1989, Jonassen, 1997; Jonassen, 2000). Problems surrounding CNSES typically related to real-world socio-scientific (at the interface of society and science) events and typically do not have correct answers. These problems are ill-structured, and add an additional layer of difficulty when combined with the five major barriers surrounding complex systems described by Herbert (2006). Existing literature included in the ''authentic complex Earth and environmental systems'' framework (Scherer et al., 2017) encompasses this type of problem-solving, but students may need support during the problem-solving process.

Goals

The previous discussion highlights significant challenges in engaging students in problem-solving in CNSES. Ill-structured problems more closely resembled real-world problems, and we suggest that it would helpful for instructors and researchers to know about the components of these types of problems. However, simply knowing the components of an ill-structured problem that surrounds a CNSES would not be useful in a classroom setting, as students would need to use practices in the process of problem-solving and may need additional classroom learning strategies and practices.

In this review article, we will achieve two main goals: (1) introduce a new model of an expanded view of the ''authentic complex Earth and environmental systems'' framework (Scherer et al., 2017) that applies the NRC (2012) Science and Engineering Practices to ill-structured problems of CNSES within a classroom centered on real-world events, (2) provide an overview of problem-solving literature in CNSES, and show specific examples of exemplary research that effectively use the components to support the use of the proposed model.

PROBLEM-SOLVING IN PRACTICE (PSP) MODEL

We propose a three-part Problem-Solving in Practice (PSP) model (Fig. 1). It has 19 unique components and four overlapping components important to student engagement with CNSES problem-solving. All components resulted from the summation of literature from the NRC (2012) Science and Engineering Practices (Table I), Jonassen's (1997) ill-structured problem components (Table II), and Herrington and Oliver's (2000) and Lombardi's (2007) learning environment practices and components (Table III). We developed the PSP model to promote a classroom environment that focuses on progressing students to expert behavior during ill-structured problem-solving. Our development of the PSP model was guided by the need to support student learning within the ''authentic complex Earth and environmental systems'' framework from Scherer et al. (2017); students must be able to relate real-world societal events with geoscience problems or challenges and suggest solutions or make decisions.

We chose to use Jonassen (1997) as the basis for the ill-structured problem components, as this is one of the most recent articles to discuss ill-structured problem components and provides a useful summary of previous work in the field; however, Voss and Post (1988) and Sinnott (1989) could also be used, as the components are similar. Initially, we sought to also use the problem-solving process from Jonassen (1997); however, when we compared this process with the NRC (2012) Science and Engineering Practices (Table I). We found that the practices aligned, but the NRC (2012) practices include additional steps (analyzing and interpreting data, the use of models and mathematical and computational thinking, and communication of results) and are more tailored towards STEM to help guide students and promote more expert-like behavior. In fact, when we examined an example of professional problem-solving in the real-world, adaptive management, we found that the steps from this problem-solving process closely matched the NRC (2012) Science and Engineering Practices and particularly highlighted engineering principles such as engineering design (Delta Stewardship Council, 2013). With the knowledge that adaptive management closely resembles the NRC (2012) engineering practices, educators may feel justified in their use of these engineering practices in the classroom. After all, the NRC (2012) practices were built from the professional experiences of real science and engineers, and so the fact

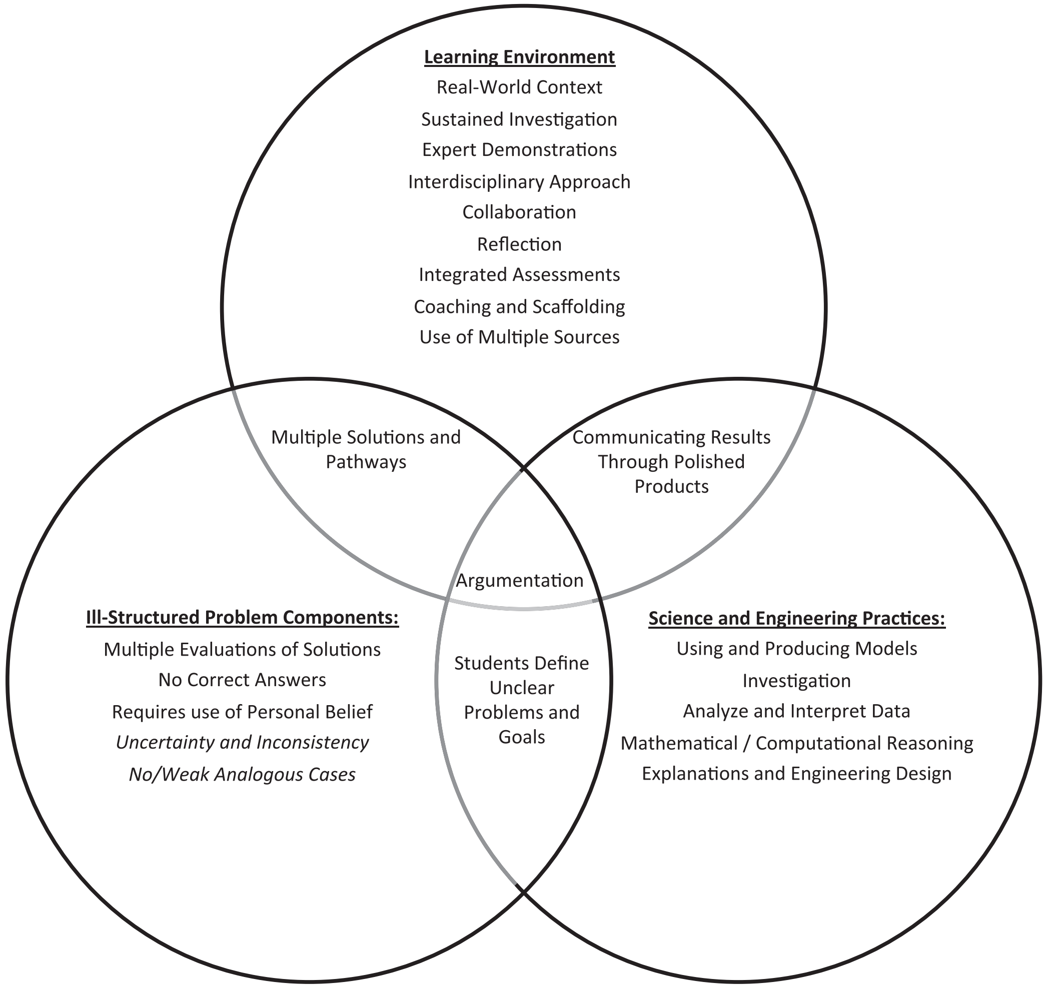

FIGURE 1: The PSP model is made up of the three spheres, including components and practices of a learning environment (Herrington and Oliver, 2000; Lombardi, 2007); ill-structured problem components (Jonassen, 1997); and the NRC (2012) Science and Engineering Practices, and also shows the overlap between the three spheres. We suggest that students apply the NRC (2012) practices to solve ill-structured problems while using specific instructor practices and student learning strategies in the classroom to foster expert-like behavior.

that adaptive management and the engineering practices look so similar is not surprising.

Jonassen's description of ill-structured problem components (Table II) was found to add key insights that were distinct from the NRC (2012) practices. The components of an ill-structured problem and the NRC (2012) practices address many difficulties students may have with the problem and the problem-solving process, but may not sufficiently support student learning of the highly complex systems geoscientists work with, which can make the process of problem-solving more difficult than in some disciplines. Therefore, we included "authentic" components of classroom, or learning environment, practices (Table III) from Herrington and Oliver (2000) and Lombardi (2007) to scaffold and impact students' affective domain and by using real-world problems and activities like reflection. We do not suggest that the components of Table III are the only way in which to represent authenticity in the classroom, but this is one of the most comprehensive lists in the literature to date (Herrington and Oliver, 2000; Lombardi, 2007; Herrington et al., 2013).

Several of the ideas from these three spheres from Fig. 1 overlap, as these concepts are related and function together. These overlapping features, including argumentation, should be considered more carefully when designing research projects or instructional activities, as they appear in multiple sources, but we advocate for researchers and instructors alike to attempt to use all 23 components (19 unique and four overlapping components) of the PSP model, from Fig. 1, to evaluate problem-solving literature and design learning activities. In the following section, we discuss each of the three spheres of the model in more detail: (1) components of ill-structured problems, (2) engaging students in the NRC (2012) Science and Engineering Practices, (3) and learning environment practices and components to enhance student interest and learning.

Problem-Solving and Ill-Structured Problem Components

Problems can be placed on a continuum from well-structured to ill-structured (Jonassen, 2004). Predominantly well-structured problems are similar to the types of problems that appear in the back of textbooks and laboratory

TABLE I: The NRC (2012) science and engineering practices explore the behaviors that experts use during scientific investigations and to explore engineering problems. Students should attempt to solve problems using these practices as they progress toward more expert-like behavior.

Category	Scientific Practices	Engineering Practices	Category
Questioning	Scientists typically begin an investigation by questioning the results of a previous experiment, or by questioning a phenomenon that is of interest.	Engineers typically begin the process of an investigation because of a need or problem that arises. They must work to define the problem by asking questions in a similar manor to scientists.	Define Problem
Producing and Using Models	Models are essential to scientists so that they can make predictions or form hypotheses about a particular question. Scientists can work with ideas and concepts that are beyond the scope of the human brain, and so models can help scientists to conceptualize a problem.	Models serve engineers by allowing them to alter constraints or to simply understand the processes and limits within a engineered system.	Using Models and Simulations
Investigation	A scientific investigation takes place to test an idea or hypothesis, support an existing theory, or to create new theories in a systematic way.	Engineering investigations typically involve the use of models to test a solution to a problem. Engineers may alter parameters and constraints to produce the best solution.	Investigation
Analyze and Interpret Data	Scientists must analyze data so that interpretations can be made about the quality of the data and the ability of the data to fit within a new or existing theory.	Engineers must analyze and interpret data to choose the most effective solution to a problem. Often, engineers must go back and forth between investigations, modeling, and analyzing and interpreting data.	Analyze and Interpret Data
Mathematical and Computational Thinking	Often, data is too complex to understand without the aid of computers and mathematical calculations, and so scientists often use these platforms to more thoroughly display and understand their data.	Engineers often base their investigations on mathematical calculations and computational models, and so engineers must be able to effectively use and edit these platforms.	Mathematical and Computational Thinking
Creating Explanations	Theories serve as the basis of scientific investigations and ideas, and experiments serve to justify or create new theories.	Engineering design is an iterative process where engineers alter parameters and constraints to find the optimal solution to a problem that takes into account engineering principles as well as monetary and safety concerns.	Engineering Design
Argumentation	Scientists must understand their data thoroughly enough to present a reasonable evidence-based argument to support any claim that they produce.	Engineers must understand their data thoroughly enough to present a reasonable evidence-based argument to support their decision-making process and the solution to a problem.	Argumentation
Communicating Results	Typically, scientists will present their work in formalized research articles, but may also present work orally, pictorially, graphically, and with the use of mathematics to disseminate their ideas and results effectively.	Engineers disseminate their research similarly to scientists to provide consumers and other researchers with details of their experiments and must vindicate their choice of solution.	Communicating Results

manuals or multiple-choice questions. These problems have a correct answer and focus on the "plug and chug" or regurgitation mentality where students must simply recall facts from memory to solve a problem; however, problems in the real world are much more complex (Simon and Gilmartin, 1973; Jonassen, 1997; Xun and Land, 2004; Jonassen, 2010). Well-structured problems are clearly less useful at gauging if a student can use and apply their knowledge to problem-solving, and for this reason, we will not include well-structured problems in the remainder of the review.

Ill-structured problems are, as the name suggests, more difficult to solve and often require mental supports, or scaffolds. The full list of ill-structured problem characteristics

TABLE II: A summary of the components of an ill-structured problem from Jonassen (1997).

Ill-Structured Problems Components	
Unclear Problem and Goals	The problem goals are stated in a way that forces students to develop a hypothesis or to define the problem
Multiple Solutions	There will be various solutions to a problem that will sufficiently address the problem because there are multiple pathways for problem-solving.
No Correct Answer	There should not be a single, convergent, correct answer, but multiple solutions that can be found through a variety of methods.
Multiple Criteria for Solution Evaluations	The problem should have multiple solutions, and as such the instructor and/or assessor will need multiple measures to evaluate student solutions.
No or Weak Analogous Cases	Ill-defined problems should not mirror previous cases, and should be considered unique, and may not use similar theories to conceptualize the problem space.
Uncertainty and Inconsistency	The problem may result in student discomfort due to the uncertain and inconsistent nature of the problem components, interactions, and rules.
Requires use of Argumentation	The problem should be framed in a way that students should engage in argumentation to fully articulate their decision-making process and must defend their solution choices
Requires use of Personal Belief	The problem promotes argumentation and decision making, and as a result students may need to assimilate and confront their personal knowledge and beliefs with the problem at hand, especially in socio-scientific situations, to defend a solution in an interdisciplinary atmosphere.

from Jonassen (1997) is summarized in Table II, and if we examine these components, we find that uncertainty is the foundation of these problems. Students are often confused by ill-structured problems because the problem itself may not be immediately visible, and students may struggle with the uncertainty of having to define a problem and the associated parameters. Ill-structured problems are also purposefully vague and open so that students may develop multiple solutions, many of which may be correct. This aspect of ill-structured problems encourages students to use arguments to support their claims, and typically these problems are framed around real-world problems that force students to challenge their personal beliefs, and often use these beliefs and previous knowledge to help justify a solution to a socio-scientific problem.

Humans are natural problem solvers, and the ability for a student to explain, think, and reason through a problem is highly sought after in both the academic and professional sector (Jonassen, 1997; Steiner and Laws, 2006; Remington-Doucette et al., 2013), but what exactly is problem-solving? Problem-solving is an activity that focuses around a central premise (a problem) where students must rely on previous knowledge, create mental models (internal representations), analyze and/or argue, and assess solutions or decisions (Jonassen, 1997).

Discomfort is common during the process of ill-structured problem-solving, and students can find ill-structured problems difficult because they often focus on the intersection of several disciplines, e.g. socio-scientific problems (Jonassen, 1997). In fact, there are several barriers that prevent students from fully conceptualizing and articulating problem complexity (Alexander, 1992; Pintrich et al., 1993). Often, when students try to recall stored information about a problem they will activate a schema, or a mental network for storing information, which can lessen the impact on working memory (Greeno, 1978; Jonassen 1997; Jonassen, 2011; van Bruggen et al., 2002). Students are able to solve simplistic problems more easily and may be able to quickly activate the problem schema; however, activating a schema for an ill-structured problem is much more difficult because the student is unlikely to have seen this type of problem before (Chi et al., 1981). Students must not only have discipline specific knowledge, but must also be able to understand the linkage of concepts and phenomena to solve a problem (Diekhoff, 1983; van Bruggen et al., 2002). The ill-structured problem component sphere is essential to the model, despite student difficulty in solving these problems, because real-world problems are typically ill-structured. Educators should give students the opportunity to practice solving these problems before entering the workforce.

Engaging Students in Science and Engineering Practices

By introducing students to problem-solving situated within CNSES to develop solutions to societally relevant problems, we expose students to professional habits from the Science and Engineering Practices in the NRC Framework (Table I). The NRC Framework (2012) emphasizes that "studying and engaging in the practices of science and engineering during their K–12 schooling should help students see how science and engineering are instrumental in addressing major challenges that confront society today, such as ... solving the problems of global environmental change" (p. 9). Although the scientific and engineering practices are typically listed together, there are some differences between the two. For example, the scientific practices are typically concerned with addressing the cause of a phenomenon, whereas the engineering practices focus on practical applications to solve problems and design solutions that impact humans and ecosystems such as agricultural runoff, eutrophication, and water management. Though some of the NRC (2012) Science and Engineering Practices differ, students should engage in both practices to be able to solve socio-scientific problems.

Students must not only define and understand the dynamics of a CNSES, but they should also be able to take the lead to address and define a problem or question and design an investigation surrounding a particular phenomenon through the construction of models and use of

TABLE III: A summary of the instructional activities, learning strategies, and instructor practices that take place in a more authentic classroom environment adapted from Herrington and Oliver (2000) and Lombardi (2007).

Instructional Activities	
Real-World Context	Students engage in activities that revolve around and closely mimic the actions of professionals in real-world situations (Herrington and Oliver, 2000; Lombardi, 2007).
Ill-Structured Problem	Instructors should immerse students within problems or activities that are ill-defined in nature and more closely resemble real-world problems (see ill-defined problem-solving table; Herrington and Oliver, 2000; Lombardi, 2007).
Multiple Sources	Students should be given a range of sources and asked to choose the relevant data, while simultaneously thinking of the problem from varying points of view (Herrington and Oliver, 2000; Lombardi, 2007).
Integrated Assessments	Assessments of student activities should be included within the activities, such as a graded final report, instead of focusing on examinations after the fact (Herrington and Oliver, 2000; Lombardi, 2007).
Sustained Investigation	Students must be involved in activities for long periods of time (typically weeks) to fully appreciate the complexity of the problem or activity (Herrington and Oliver, 2000; Lombardi, 2007).
Interdisciplinary Approach	Activities should include aspects of other disciplines, requiring students to think beyond one discipline, typically in a socio-scientific context (Lombardi, 2007).
Multiple Solutions and Pathways	Authentic activities should produce multiple solutions to a problem, because there are typically multiple ways to solve a problem, and in a real-world situation there will likely be multiple solutions that solve a problem (Lombardi, 2007).
Learning Strategies	
Collaboration	Experts in almost every field work in groups to solve problems, and so the learning environment should reflect the nature of the workplace (Herrington and Oliver, 2000; Lombardi, 2007).
Reflection	Reflection gives students the opportunity the think about their choices, to consider other perspectives, and to consider future implications of the activity (Herrington and Oliver, 2000; Lombardi, 2007).
Articulation and Argumentation	Students should be able to write and speak about their choices during an activity and to defend any decisions that were made during the process (Herrington and Oliver, 2000).
Polished Product	Students should create a final report, presentation, or any other finalized product to summarize their experience, decision making process, and provide additional opportunities for reflection (Herrington and Oliver, 2000; Lombardi, 2007).
Instructor Practices	
Expert Demonstrations	Experts, ranging from instructors to guest speakers, should model their behavior so that students may learn from example by following the tenants of cognitive apprenticeship (Herrington and Oliver, 2000).
Scaffolding	Coaching and scaffolding are important for novice students because they may not have all of the necessary disciplinary knowledge and experience that a professional would (Herrington and Oliver, 2000).

computational or mathematical thinking to make decisions and to support an explanation, solution, or justification. Furthermore, by following the NRC (2012) Science and Engineering Practices, students begin to develop expert behavior such as analyzing and interpreting data to be able to synthesize and make conclusions, explaining or developing solutions (engineering design) so that students can consider multiple solutions and make decisions, argumentation to explain why a particular solution was justified, and communicating results to summarize the previous steps (NRC, 2012). If we want our students to progress toward expert behavior, we should allow them to engage in practices that experts use, and the ability to use and produce models may be one of the most important practices from the NRC (2012) when working in CNSES.

Models are especially helpful in the geosciences because we discuss many concepts, such as complex systems, which are outside of human conceptions of time, spatial abilities, and pattern recognition (Herbert, 2006; Orion & Ault, 2007). Solving an ill-structured problem in a CNSES requires the development of a sophisticated and robust mental model that typically relies on some type of external representation (model) to reduce the cognitive load on working memory (van Bruggen et al., 2002). A student may generate a reasonably accurate model of a system, whether mental or external, and that model then becomes the basis for engineering design. In this way, a student or professional could take this model and identify needs (function, constraints, tradeoff), plan investigations from these models, and reason from these models (model-based reasoning) to support solutions through argumentation.

Learning Environment Practices and Components

Certain practices, strategies, and concepts (or elements) in the classroom may help to enhance student learning, motivation, and engagement. Herrington et al. (2013) suggest the use of "authentic learning" elements in the classroom and define authentic learning as "a pedagogical approach that situates learning tasks in the context of real-world situations, and in so doing, provides opportunities for learning by allowing students to experience the same problem-solving challenges in the curriculum as they do in their daily endeavors" (p. 401).

Herrington and Oliver (2000) and Lombardi (2007) have identified several promising classroom elements that may encourage more authentic behavior (Table III). Typically these practices and components of the learning environment are given as an uncategorized list, but we have chosen to separate out the components into three parts including: (1) instructor practices, (2) instructional activity components, and (3) learning strategies.

As educators, we should model our practices on how experts behave during problem-solving as Macfarlane et al. (2006) suggest we should "model how an environmental consultant would apply these concepts to the resolution of a . . . problem," and "provide the student with training . . . used by an environmental consultant under real-world conditions and thus helps them conditionalize their knowledge" (p. 612). Instructor practices focus around scaffolds that take place in the classroom to ease students' lack of prior knowledge or experience. Instructors can help to model expert practices through cognitive apprenticeship (a master teaches a novice) so that students can emulate expert-like behavior (Collins et al., 1987; Herrington and Oliver, 2000; Lombardi, 2007; Herrington et al., 2013). Instructors also use various components of instructional activities in an effort to make their classroom more authentic. A real-world context is one of the most important components of an instructional activity, and the NRC (2017) support this by suggesting that problems or research should "focus on significant, relevant problems of interest to STEM researchers and, in some cases, a broader community" (p. 2-2). Many of these components are meant to increase student engagement, like the use of real-world problems and a multidisciplinary approach to tie science to society. Student interest in a real-world problem, especially one that contributes to their well-being or daily life, can contribute to greater impact learning around ill-structured problems, as students are more motivated to solve a problem with a personal connection to themselves and their communities (Bransford et al., 2000; Gilbert, 2006; Sawyer, 2006; Duschl, 2008; McConnell and Van Der Hoeven Kraft, 2011; NRC, 2012). Learning is often situated in the preexisting student knowledge, and so past experiences and beliefs play a role in the cognitive processes that occur during problem-solving (Rogoff, 1990; Lehrer & Schauble, 2006; Duschl, 2008).

Finally, the learning strategies introduced by Lombardi (2007) and Herrington and Oliver (2000) match several of the characteristics of undergraduate research laid out by the NRC (2017) including collaboration so that students could be exposed to a variety of diverse ideas and opinions, student reflection to promote metacognition, argumentation during the activity to summarize and defend a student's solution choice, and the production of a polished product to summarize learning. If we combine the three parts of the practices and components of the learning environment (instructional activities, learning strategies, and instructor practices), many of which align with the NRC (2017) characteristics of undergraduate research, we can develop a description of how to transition a traditional classroom into a more authentic learning environment as shown in top sphere of the PSP model.

In the following sections we will apply the PSP model to literature in the field of moderate to ill-structured problem-solving surrounding CNSES. We provide the reader with examples of exemplary research that use components of the model to scaffold students toward expert behavior in the classroom. Additionally, we will discuss the implications of underused and overlapping components of the model.

METHODOLOGY

To understand how well the PSP Model resonates with the current literature, we conducted a review of literature that address ill-structured problem-solving in the geosciences. To review student problem-solving around CNSES, we used key-words "problem-solving, or decision making, or problem-based learning, or inquiry-based learning" combined with "geoscience or geology." We examined a cross-section of journals including the International Journal of Science Education, the Journal of Science, Education, and Technology, the Journal of College Science Teaching, the Journal of Research in Science Teaching, the Journal of Geography in Higher Education, and preferential selection from the Journal of Geoscience Education as this journal primarily serves the geoscience community. Initially, we compiled over 150 papers that involved some combination of the previously stated key words, and so to reduce this number we selected papers that met certain criteria.

Ill-structured problem-solving has been a key theme throughout this literature review, and as such we wanted research that reflected the nature of problem-solving in real world applications. For example, we eliminated literature that predominantly focused on multiple choice assessments of problem-solving, because these well-structured problems do not mimic expert problem-solving practices as laid out by the NRC (2012) and Jonassen (1997). Additionally, we screened the literature to limit research that delved into student misconception and specific student Earth systems thinking skills, as we are interested in how students apply their knowledge to problems. The second criteria excluded literature on elementary age children, as the focus of this paper is on ill-structured problem-solving in CNSES, and we felt that the literature at that level would not be able to focus on a complex topic (CNSES) because students at this age would not have the necessary background. The selected literature also had to contain student data, because without it, we would not be able to report on the use of integrated assessments. Finally, we excluded literature that primarily focused on the interactions between wildlife and the environment, because although we advocate for an interdisciplinary approach to problem-solving, this literature review is intended to focus on the contribution from the geosciences as opposed to ecology. In summation, the following section of this review describes the state of knowledge in the field of problem-solving in CNSES by students that range from middle school to higher education, including student assessments or data, and must focus on geological processes as opposed to animal or plant behaviors. By introducing these review parameters, we reduced the relevant literature in the CNSES problem-solving field ($n = 11$) (Table IV).

The first author, Holder, used the PSP model as a rubric to analyze and categorize each of the 11 papers, and to evaluate the usefulness of the model when applied to

TABLE IV: Titles of papers included in the review of problem-solving in the geosciences. The paper number corresponds with the paper numbers from Table V.

Paper Number	Paper title	Author
1	Introducing transdisciplinary problem-solving to environmental management systems and geology students through a case study of disturbed coastal systems	Walsh and Wicks (2014)
2	Concept mapping to reveal prior knowledge and conceptual change in a mock summit course on global climate change	Rebich and Gautier (2005)
3	Supporting student conceptual model development of complex Earth systems through the use of multiple representations and inquiry	Sell et al. (2006)
4	Inquiry in the physical geology classroom: Supporting students' conceptual model development	Miller et al. (2010)
5	Teaching Environmental Geochemistry: An Authentic Inquiry Approach	Koretsky et al. (2012)
6	Problem-based learning approaches in meteorology	Charlton-Perez (2013)
7	Model my watershed: Connecting students' conceptual understanding of watersheds to real-world decision-making	Gill et al. (2014)
8	Using problem-based learning to bring the workplace into the classroom	Dadd (2009)
9	Linking biophysical, socioeconomic, and political effects of climate change on agro-ecosystems	Balgopal et al. (2014)
10	A problem-based learning exercise for environmental geology	Lev (2004)
11	Helping students make the transition from novice learner of ground-water concepts to expert using the plume busters software	Macfarlane et al. (2006)

relevant literature in the CNSES field. Holder assessed commonly used strategies, practices, and problem components during problem-solving using 21 of the 23 identified characteristics from the PSP model (Fig. 1). Two of the components (uncertainty and inconsistency and no analogous cases) were not included because these were difficult to assess in the majority of the literature because the majority of the articles did not mention these factors specifically. Each article was marked as "Yes" if the article demonstrated the characteristic in question, "No" if the article specified that they had not used one of the characteristics, or "N/A" for not available if the article did not specifically address or was unclear about the component or practice (Table V).

RESULTS OF ALIGNMENT OF THE PSP MODEL WITH EXISTING LITERATURE

In the following sections, we have categorized the selected literature ($n = 11$) (Table IV) to validate the PSP model and discuss commonalities of the literature, including the topic of the learning activities. Of the 11 papers, three focused on climate change (Rebich and Gautier, 2005; Charlton-Perez, 2013; Balgopal et al., 2014), five focused on watershed contamination and management (Lev, 2004; Macfarlane et al., 2006; Dadd, 2009; Koretsky et al., 2012; Gill et al., 2014), and three touched on coastal issues such as eutrophication, coastline migration, and wetland management (Sell et al., 2006; Miller et al., 2010; Walsh and Wicks, 2014). For organizational ease, we have divided the following sections into the components of the PSP model.

PSP Model: Learning Environment

As Gill et al. (2014) suggests, "Using students' 'home turf' as the object of exploration provides context and relevance that enhance engagement and promote meaningful learning" (p. 61). Additionally, much of the problem-solving literature contained authentic (real) data (Sell et al., 2006; Dadd, 2009; Miller et al., 2010; Koretsky et al., 2012; Gill et al., 2014; Walsh and Wicks, 2014) and encouraged the use of role-playing activities to increase student engagement (Lev, 2004; Rebich and Gautier, 2005; Macfarlane, 2006; Sell et al., 2006; Dadd, 2009; Charlton-Perez, 2013; Balgopal et al., 2014; Gill et al., 2014; Koretsky et al., 2014; Walsh and Wicks, 2014).

Nine of the 11 articles focused on data uncertainty and the use of multiple sources during problem-solving. For example, Macfarlane et al. (2006) "...attempted to introduce levels of uncertainty in the data to make the simulations more realistic" because "an environmental consultant must rely on uncertain knowledge" (p. 612). Group work and collaboration was also a component of the model, and typically students were encouraged to engage in group work ($n = 10$). To increase students' knowledge base, experts or professionals contributed in only three of the 11 articles: to the generation of instructional materials (Dadd, 2009), supplied reports (Macfarlane et al., 2006), and gave lectures like in the case of Walsh and Wicks (2014), where guest speakers included "a geologist researching Louisiana's deltaic systems, a wetland ecologist specializing in coastal restoration, and a landscape architect working on Louisiana's 2012 Coastal Master Plan" (p. 49).

Only four of the selected papers used a multidisciplinary approach to frame a problem from multiple perspectives. Additionally, reflection was one of the smaller categories with only five articles. Even though one article, Koretsky et al. (2012), discussed student reflection during interviews, we chose to mark this article as "no" for reflections because the entire class did not participate and the reflection was not built into the activity.

Often, formal presentations, reports, and other polished products served as a means of integrated assessment ($n = 9$)

TABLE V: 21 unique (non-overlapping) features compiled from the PSP model and applied to problem-solving literature. The PSP model was derived from the NRC (2012) science and engineering practices, an authentic learning environment, and components of ill-structured problems (Herrington and Oliver, 2000; Lombardi, 2007; Jonassen, 1997). The numbers in each box correspond with a paper, which is shown in the far right box. If a paper is located within the "Yes" column, then the paper has the component, if "No" then the paper does not contain the component, and "N/A" suggests that the paper did not discuss the component. Each paper is represented by a number: (1) Walsh and Wicks, 2014, (2) Rebich and Gautier, 2005, (3) Sell et al., 2006, (4) Miller et al., 2010, (5) Koretsky et al., 2012, (6) Charlton-Perez, 2013, (7) Gill et al., 2014, (8) Dadd, 2009, (9) Balgopal et al., 2014, (10) Lev, 2004, and (11) Macfarlane et al., 2006.

	Yes	No	N/A
Components of Problems (Jonassen, 1997)			
Multiple Evaluations of Solutions	1, 2, 3, 4, 5, 6, 7, 8, 9, 11		10
No "Correct" Answers	1, 2, 3, 4, 5, 7, 8, 9	6, 10, 11	
Requires Expression of Personal Beliefs and Opinions	2, 7, 9.	11	1, 3, 4, 5, 6, 8, 10
Authentic Learning Environment (Herrington and Oliver, 2000; Lombardi, 2007)			
Real-World Relevance	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11		
Sustained Investigation	1, 5, 6, 8, 10	2, 4, 9, 11	7, 3
Expert Performance and Modeling	1, 5, 8,	2, 3, 4, 9, 10, 11	6, 7
Interdisciplinary Approach	1, 2, 7, 9	3, 4, 5, 6, 8, 10, 11	
Collaboration	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	11	
Reflection	2, 3, 4, 6, 7	1, 5, 8, 9, 10, 11	
Coaching / Scaffolding	2, 3, 4, 5, 7, 8, 9	6, 10, 11	1
Integrated Assessments	1, 2, 3, 4, 5, 6, 8, 9, 10	7, 11	
Use of Multiple Sources	2, 3, 4, 5, 7, 8, 9, 10, 11		1, 6
Science and Engineering Practices (NRC, 2012)			
Model Production	2, 3, 4, 5, 7, 10, 11	9	1, 6, 8
Analyze and Interpret Data	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11		
Use of Mathematical or Computational Representations	1, 3, 4, 5, 7, 9, 10, 11		2, 6, 8
Designing Solutions (Engineering Design)	4, 6, 7, 10, 11	2, 5, 9	1, 3, 8
Planning Investigations	1, 2, 3, 4, 5, 6, 7, 8, 10		11, 9
Overlapping Components			
Argumentation	2, 4, 5, 7, 9, 10	11	1, 3, 6, 8
Unclear or Unknown Problem and Goals	3, 4, 8	1, 2, 5, 6, 7, 9, 10, 11	
Multiple Solutions and Pathways	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11		
Polished Product	1, 2, 3, 4, 5, 6, 8, 10, 11	9	7

for problem-solving and student learning. Coaching and scaffolding are the last of the learning environment components, including the amount of instructor given aid for the problem-solving process (e.g., Did the students receive explicit instruction in the steps of problem-solving including the production or use of a model?), and more generalizable scaffolds to decrease the cognitive difficulty when using instructional technologies (IT), dealing with complex systems, and to generally increase student engagement in the topic. IT expertise was explicitly and implicitly suggested as a scaffold for interpretation and understanding of graphs, large data sets, and software manipulation (Sell et al., 2006; Miller et al., 2010; Macfarlane et al., 2006; Gill et al., 2014). For example, Gill et al. (2014) conducted a pilot study and found that students saw a large disconnect between classroom instruction and the Model My Watershed application, and so during the next iteration of the course the instructors incorporated more hands-on experience with the application within the curriculum. Domain expertise was also a common thread throughout the literature, because students must have a strong knowledge foundation about the topic in question, but also how these facts are connected to larger concepts (Diekhoff, 1983). Rebich and Gautier (2005), Sell et al. (2006), Dadd (2009), Miller et al. (2010), Koretsky et al. (2012), Charlton-Perez (2013), and Walsh and Wicks (2014) emphasize this foundation and often held tutorials or help sessions to ensure that the students had a similar knowledge base. Finally, multiple representations appeared in nine of the selected papers in the form of physical models, graphs, pictures, computer simulations, and drawn models, and will be discussed in further detail in the modeling section (Lev, 2004; Rebich and Gautier, 2005; Macfarlane et al., 2006; Sell et al., 2006; Dadd, 2009; Miller et al., 2010; Koretsky et al., 2012; Gill et al., 2014; Balgopal et al., 2014).

PSP Model: Ill-Structured Problem Components

Each of the surveyed papers used multiple methods to evaluate their students. Evaluation ranged from rubrics to quantify student progress, pre- and post-tests, vetted assessments such as Draw My Watershed (Gill et al., 2014), and interviews and focus groups. Additionally, in almost all cases there was no "correct" answer to a problem during assessments, but, for example, Macfarlane et al. (2006) suggest that there are a range of correct answers within a small spectrum, and so this article failed to meet the requirements for the "no correct answers" component of the model.

Because these problems are so complex, students must often rely on prior knowledge and personal beliefs in order to argue for their solutions to problems. Gill et al. (2014) highlights that social impacts must be considered, which is another key component of ill-structured problems, according to Jonassen (1997). This was one of the most difficult components to assess throughout the literature, because often the author alluded to the use of personal beliefs, but never explicitly discussed this premise. Only three articles suggested that students should use their personal beliefs or opinions to help solve a problem (Rebich and Gautier, 2005; Balgopal et al., 2014; Gill et al., 2014).

PSP Model: Scientific and Engineering Practices

Although the scientific and engineering practices post-date most of the papers in this review, what is clear is that even though they are not explicitly called out, all of the papers incorporate a number of the practices. All of the surveyed articles encouraged students to manipulate or analyze data. On the other hand, the least used practice was designing solutions (or engineering design), with only five out of the 11 papers. The use of mathematical or computational modeling ($n = 8$), the production of models ($n = 7$), and modeling in general were prevalent themes throughout the selected literature. In several cases, students were able to access large data sets to manipulate either computerized simulations like Model My Watershed (Gill et al., 2014) or Plume Busters (Macfarlane et al., 2006), manual simulations (like Excel, GIS; Sell et al., 2006; Miller et al., 2010), conceptual models and box models (Lev, 2004; Rebich and Gautier, 2005; Sell et al., 2006; Miller et al., 2010; Koretsky et al., 2012), or maps, existing graphs, and figures. The last practice involves planning investigations. Almost every paper ($n = 9$) encouraged students to pursue their own investigation of the material, and the other two papers, which were marked "N/A", did not detail their students' pathway through the activity.

Overlapping Components

The following four components appeared in two or more of the spheres from the PSP model: argumentation, unclear problems and goals, multiple solutions and pathways, and the production of polished products. One of the most surprising findings from this review was the presence of multiple solutions and pathways from all of the selected literature. This was surprising because three of the selected articles had a correct answer to their problem, but instructors often allowed students to plan an investigation to solve problems in a variety of ways. So, though students were intended to converge upon one answer, the pathway could vary from student to student. Argumentation, as previously discussed, may be a crucial component of learning, especially within CNSES because this was the only practice or component that was present within each of the three spheres from the PSP model. However, argumentation was only explicitly discussed by six of the articles.

Within the overlapping components, polished products was a common theme among the selected literature ($n = 9$) and although one of the selected papers, Balgopal et al. (2014), supported classroom discussions, the students did not make a formal presentation and so we did not classify this as a polished product. Unfortunately, only three of the cases allowed students to define the problem at hand, and instead, in eight of the articles the instructor provided the students with the problem and often contributed data, especially in the case of a fictitious site or phenomenon. Even in cases where students were able to collect their own authentic data in the field, for example Koretsky et al. (2012), the problem was moderately ill-structured because of the nature of the laboratory course where the problem was clearly stated "can a eutrophic lake be remediated?" (p. 315), but how this remediation would take place would be left to the students.

DISCUSSION AND EXEMPLARS

In this section, we discuss each of the three components of the model in the context of exemplars from the literature.

Science and Engineering Practices

Lev (2004), Miller et al. (2010), and Gill et al. (2014) used all of the unique (non-overlapping ideas from the PSP model) NRC (2012) Science and Engineering Practices from Table V. Lev (2004) promotes a fictitious, local, role-playing environment that focuses around an environmental cleanup effort where students function as a "project manager for the Maryland Department of the Environment, a consultant for the principle responsible party (PRP), or a consultant hired by the community" (p. 128). Students were given introductory data about the spill, selected resources and encouraged to look elsewhere for additional sources of information, and a budget to remediate the spill of PCBs and other chemicals. This budget provides some constraints to the problem and allowed for students to plan their investigation around these constraints and to also use engineering design to iteratively analyze and interpret data to identify a solution that takes constraints and parameters into account. The students were asked to produce a model of the chemical plume, reason from this model to support the expenditures that they suggest, and to argue their stance during the "presentation and justification of the phase II work plan" (Lev, 2004, p. 129). The problem from the instruction activity may not be completely ill-structured, as the rubric for assessment suggests that there is a correct answer, and does not require students to use their personal beliefs, but this paper demonstrates strong use of the NRC (2012) Science and Engineering Practices.

Gill et al. (2014) similarly used the five unique NRC (2012) Science and Engineering Practices to approach the management of water resources. The activity design encourages the use of a data analysis and interpretation through computer simulations to produce models that were then used to suggest solutions to a problem. Students did not collect the data, but were able to manipulate various parameters within the simulation to argue for their solution to three problems and to use best-management practices, or adaptive management. Students used adaptive management, which is similar to the NRC (2012) practices, to encourage sustainable growth within the community, minimize flooding and stabilize a river using a risk assessment, and reduce storm water runoff. Students were encouraged to test out solutions through investigations, and then to redesign their simulation to improve possible solutions through engineering design.

Miller et al. (2010) was a third author who incorporated all of the unique NRC (2012) Science and Engineering Practices into their classroom. Students in an introductory geology course were able to directly manipulate and represent large data sets through the use of Excel and through the use of a physical model, plan their investigation, analyze data, and to create pre- and post-conceptual models. The researcher also allowed their students to reflect throughout the process, and as a result students were able to engage in engineering design to alter their ideas about the data and physical model. Finally, the instructor used integrated assessments to rate students' ability to argue their point, understanding of scale and systems processes, as well as a variety of other measures.

In fact, the majority of the articles used the NRC (2012) Science and Engineering Practices, although analyzing and interpreting data was the most common, following by planning investigations; the least used practice was engineering design. This iterative process may be difficult to incorporate into the classroom unless, for example, a class works on a problem or activity for long periods of time and is given the chance to reflect upon their work to reformulate solutions. Without incorporating aspects of the practices and components of the learning environment, students may not easily be able to work through solution design. We have chosen to break out models from the main NRC (2012) Science and Engineering Practices to discuss this component more thoroughly because we believe that models are of crucial importance when dealing with CNSES.

Models

As previously discussed, models and model-based reasoning is of vital importance when dealing with complexity of near-surface earth systems and every selected paper except for Charlton-Perez (2013) and Dadd (2009) explicitly included students' use of models, either student-constructed or through the use of mathematical and computational representations. Nine papers used some combination of model production or the use of pre-existing models, and we suggest three of these papers as exemplars: Macfarlane et al. (2006), Sell et al. (2006), and Gill et al. (2014). Gill et al. (2014) and Macfarlane et al. (2006) detailed student modeling through the use of computer simulations to "give students the ability to manipulate data with the click of a mouse" (Gill et al., 2014, p. 61). In all three of these cases, students were expected to directly manipulate and reason from the resulting models, just as an expert would. In fact, Macfarlane et al. (2006) suggests that "to be successful the consultant must possess both an understanding of the scientific issues involved in resolving contamination problems and be able to provide services to the client in the most cost efficient manner" (p. 612). This linkage between the scientific issues and the solution comes from the manipulative model, because without this crucial step the students would not be able to visualize the complexity of the environment and use model-based reasoning to support solutions to problems. In fact, Macfarlane et al. (2006) goes as far to suggest "students are seldom presented with models of how an environmental consultant (the expert) uses science to solve real-world contamination problems. Simulations and role-play are effective means by which we help novice learners to move toward the expert level" (p. 619).

Sell et al. (2006) also used models to allow students to justify scientific claims and to link these to environmental management problems; however, unlike the previous exemplars, these models included self-constructed conceptual models, physical models, and data-driven models from Excel. Sell et al. (2006) implies that models can be used as a scaffold and that instructors should "provide more opportunities for students to express, share, and discuss their external conceptual models, more immediate feedback to students, and more time for reflection and revision of internal mental models" (p. 405). Sell et al. (2006) incorporated the use of multiple representations, which has been linked to improved student understanding, metacognitive development, and ability to make connections from mental or conceptual models to the real world (Boulter and Gilbert, 2000; Buckley and Boulter, 2000). Additionally, by encouraging the use of expressed (written, drawn, etc.) conceptual models, Sell et al. (2006) could easily assess if students maintained misconceptions throughout the learning process (Ainsworth, 2008; Köse, 2008; Cooper et al., 2009).

Expressions of internal mental models, it could be argued, are just as important as using a preconstructed model of a complex system, since internal models may hold the key to understanding (Johnson-Laird, 1983). Self-constructed or manipulative models also allow students to revise their work, reflect upon this work, and encourage iterative behavior, which is at the heart of the NRC (2012) engineering practice of designing solutions. CNSES are complicated and involve interactions that are far beyond the comprehension of the human mind, just like many ill-structured problems, and so researchers, professionals, and students alike must reduce the cognitive load on their working memory to be able to work through problems (van Bruggen et al., 2002). Representations, or models, are one way, whether mental, physical, drawn, written, gestured, or spoken, that can help to reduce the effort of using of working memory (Larkin and Simon, 1987; Zhang and Norman 1994; Waldrip and Prain 2013). Knowing this, instructional design should place an emphasis on model recognition, creation, and understanding, especially when dealing with ill-structured problems in CNSES.

Practices and Components of the Learning Environment

Rebich and Gautier (2005), Dadd (2009), and Koretsky et al. (2012) and each used eight of the 10 practices and components of the learning environment. Of these three exemplars, only Rebich and Gautier (2005) successfully used a multidisciplinary approach, only Koretsky et al. (2012) and Dadd (2009) provided their students with access to expert modeling, only Koretsky et al. (2012) and Dadd (2009) supported sustained investigations, and only Rebich and

Gautier (2005) promoted reflection in their course. Otherwise, these three exemplars tried to frame their group activities around real-world problems ranging from water quality to climate change and tried to make the activities as authentic as possible by using multiple resources, although Rebich and Gautier (2005) were the only authors in our exemplars that encouraged students to seek outside sources.

Each of these exemplars also included integrated assessments of student learning and problem-solving in final reports and presentations. For example, Rebich and Gautier (2005) propose that, "students are evaluated on the basis of performance on presentation, writing and negotiation activities… [and] no tests are given as part of the course, and the final means for evaluation is the quality of the final agreement negotiated by the class" (p. 358). Koretsky et al. (2012) used triangulation and a mixed-method approach to assess the student learning outcomes by using knowledge pre- and post-tests, student report analysis, interviews, student evaluations of the course, and post-interviews. The pre- and post-tests were common throughout the literature to assess background knowledge and attempted to measure learning gains as a function of an intervention, but Koretsky et al. (2012) stands out because of the mixture of different interviews, analysis of student artifacts, and student evaluation so that students could reflect on the nature of their learning to help ensure that changes could be made to enhance the learning potential of the instructional materials. Rebich and Gautier (2005) took a different approach to integrated assessments by using concept maps that allowed the students to reflect on the activity and allowed the instructor to evaluate learning outcomes. Reflection is an important practice in the classroom, and helps during the development and reformulation of ideas, and so reflection can occur at the end of a course in the form of an interview or a final report (Herrington et al., 2013), but can also be encouraged throughout the learning process, especially during problems that take place over extended periods of time (a semester or more). Additionally, all three exemplar articles provided coaching and scaffolding to encourage student understanding of the underlying disciplinary material. For example, Dadd (2009) introduced a "lecture series giving background material and a series of guides that set the problem context and give direction" (p. 1).

Dadd (2009) chose to frame their ill-structured problem around environmental remediation and risk management. Experts were brought in to develop various instructional materials and students went into the field to get first-hand experience at a mine site. Consequently, students are able to not only act like scientists in the field to collect authentic data, but were also able to work together to use this data to support a final environmental assessment of the area over the course of several weeks. The author suggests that they scored final reports and presentations, as well as an open-ended exam question that mimicked students' in-class activities. Despite this, the author provided only student self reports as a measure of problem-solving abilities.

Koretsky et al. (2012) used the problem of local water quality as the focus for a semester-long project. The students worked in teams and learned laboratory techniques from the instructor, and also received weekly feedback and coaching to complete an assessment of the local water quality. Students were exposed to multiple sources of information throughout the semester, and created a final report and presentation, and actually gave this public presentation in a local brew pub. Additionally, the students were assessed using their reports, interviews, course evaluations, and pre- and post-knowledge tests. Koretsky et al. (2012) was one of the few articles that focused around an entire semester and according to Herrington and Oliver (2000), an authentic instructional activity should last for, at the very least, longer than a class period. Typically, problem-solving takes much longer than one short class to fully evaluate solutions and to effectively reflect and write about the experience in the form of a report, video, presentation, or other polished product.

Finally, Rebich and Gautier (2005) used a role-playing exercise focused around climate change where teams of students acted as representatives from various countries and different disciplines to eventually create a document similar to the Kyoto protocol. To increase student awareness, the instructors suggested that the students should produce concept maps as a means of reflection before and after the activity and used these concept maps as a form of assessment along with a pre- and post-test and post questionnaire. Additionally, instructors strove for an authentic learning environment by requiring students to produce a final Kyoto protocol document by using instructor given and student found resources and providing adequate coaching for students by "provid[ing] individualized written feedback to the students to help them improve their research and related writing and presentation assignments" (Rebich and Gautier, 2005, p. 358).

In summation, all of the selected literature framed problems around real-world events and commonly focused on the use of collaboration, multiple sources, coaching and scaffolding, and integrated assessments. The least used components were access to expert performances, a multidisciplinary approach, sustained investigations, and reflection. We suggest that instructors try to use all of these practices in order to reduce differences in the classroom like background knowledge and enthusiasm about the course or problem.

Components of Ill-Structured Problems

Rebich and Gautier (2005), Gill et al. (2014), and Balgopal et al. (2014) all used ill-defined problems that contained all of the unique (did not overlap with other parts of the PSP model) components of ill-structured problems. Each of these exemplars had multiple ways of assessing the solutions, had no correct answer to their problem, and cited the use of personal beliefs or opinions for students to solve a problem. The majority of selected literature neglected the use of personal belief or opinions, and future researchers should adjust their curriculum to allow this type of thinking within socio-scientific classrooms. Instructors must be sure to account for prior beliefs and knowledge, and must understand that many student beliefs are situated it their past experiences, and this can be difficult to separate from the learning process (Duschl, 2008). Instead of banning the use of personal belief, students should support their arguments with evidence, and then use this evidence to reframe or justify their beliefs, especially in socio-scientific arguments. Balgopal et al. (2014) advocate for the use of student beliefs, but also recognize that students must use evidence-based claims to support these beliefs: "The majority of the claims were supported by a combination of different types of evidence, including personal knowledge, personal experience or experiences from the class discussion, data presented as part of the activity, and beliefs" (p. 348).

These exemplar articles also advocated for the use of multiple evaluations of solutions and had open-ended problems that did not direct students towards a "correct" answer. Gill et al. (2014) framed their activities so that "students are asked to justify their decisions and to discuss how they are addressing local societal and economic issues in a culturally sensitive way" (p. 65). This open and ill-structured problem allows students to consider many pathways for the solution because they must consider societal, economic, and geological data to suggest a solution. Similarly, Balgopal et al. (2014) indicated that to find a solution to a problem, a student must "... recognize the multidimensionality of managing rangelands within the context of a changing climate when different stakeholders' perspectives are considered, (2) decisions cannot be made without relevant evidence, and (3) maintaining the ranching/pastoral way of life in the face of climate change will require adaptation, learning, and adjustments" (p. 349). The open nature of this problem allowed the instructor to evaluate students through various measures including classroom discussion and observation and written assessments with an emphasis on the types of data that students used to justify their actions. The problem allowed for a variety of solutions and there were no "correct" answers because of the number of variables that students had to use in their decision-making process. As instructors, these problems may be more difficult to evaluate, but Balgopal et al. (2014) make an excellent case for the use of evidence to support student claims as one of the ways to assess solutions to problems.

Almost all articles evaluated students' solutions in multiple ways ($n = 10$) and had no "correct" answers ($n = 8$). However, few articles encouraged the use of personal opinions or beliefs ($n = 3$), because as scientists we want our students to use evidence-based claims; however, when students are involved in socio-scientific problem-solving, especially surrounding CNSES, the solution may change as a function of student's morals and beliefs. Often, there are no "right" answers to a solution in the real world, and people should use evidence to support their claims, but sometimes a solution arises from building upon evidence, previous experiences, and personal beliefs (Meacham & Emont, 1989; Jonassen, 1997). This is not to say that we recommend students use personal beliefs as the basis for their argument, in fact, we recommend that students always use evidence-based arguments, but when problems arise at the interface of science and society, a problem may not be solved using science alone.

Overlapping Components of PSP Model

Miller et al. (2010) was the only article that contained all four of the overlapping components from the PSP model including argumentation, unclear problem and goals, multiple solutions, and polished products. Additionally, Miller et al. (2010) had the highest number of features of the selected components ($n = 17$ of 21) from the PSP model. The only aspects of the model that were not present were the requirement for the use of personal beliefs or opinions, a sustained investigation, access to expert performance and modeling, and a multidisciplinary approach. The remaining three model components that were missing came from the practices and components of the learning environment sphere. The components and practices of a learning environment offer guidelines for instructors, but they may not be applicable to all cases during problem-solving. For instance, sustained investigation during problem-solving is a goal because students are able to fully explore and articulate a problem over a long period of time, typically a semester, but this is often difficult to achieve in a more traditional classroom. Miller et al. (2010) focused on an introductory laboratory class with changing topics from week to week, and so the implementation of a semester-long project was not as feasible as in other classroom settings.

Miller et al. (2010) used a rigorous rubric to evaluate argumentation and critical thinking: "Evidence is linked to explanation. Uses logic to describe the system much like that of a scientist" (Miller et al., 2010, p. 605). Not only did the authors support evidence-based argumentation, but they also suggested that students could suggest multiple solutions, "formulate a hypothesis centered on their investigation of shoreline dynamics and sand transport" (p. 601) instead of providing the students with a hypothesis at the beginning of the laboratory, and encouraged the production of a polished product in the form of written report, but also through the use of student generated conceptual models.

Student-generated models and written reports allowed students to summarize the activity, and also gave the students a chance to "... revise their thoughts throughout the process giving them the chance for reflection and revision" (Miller et al., 2010, p.601) Self-constructed or manipulative models also allow students to revise their work, reflect upon this work, and encourages iterative behavior, which is a tenet of engineering design. Students would have the chance to change their external model or solution to reflect their changing mental model, thus making their reasoning visible. By combining both a student generated model and written reports, Miller et al. (2010) was able to evaluate student learning and understanding of complex systems through the use of a rubric, which was based upon Chinn and Malhotra (2002) and was validated by 14 external evaluators. In fact, they showed that the students involved in the experimental group showed measurable gains in critical thinking, which the author attributes to students' ability to directly manipulate a physical model, computational model, and student's ability to learn through inquiry to design their own experiments. Students were guided toward the use of all of the NRC (2012) Science and Engineering Practices and students were able to interact with a problem that met all but one of the components of ill-structured problems (use of personal belief).

IMPLICATIONS AND SUGGESTIONS FOR FUTURE WORK

We suggest that the PSP model serves a basis for both research and instructional design within the classroom at a variety of levels when working with problems surrounding CNSES. Instructors can use the model to improve upon existing curriculum or build new curriculum units by using the model as a rubric to guide specific practices and strategies in the classroom. Additionally, researchers can use the model to study the combined impact of practices, strategies, and components of ill-structured problems. There is no "correct" method to use this model, as the spheres are interrelated, but it may be helpful for instructors and researchers to begin with the components of ill-structured problem(s), move on to the implementation of the NRC (2012) Science and Engineering Practices in the classroom, and finally use elements of an authentic learning environment to scaffold students. As previously noted, not all elements of the learning environment may be useful in every classroom, but we suggest that these practices can help alleviate problems that arise from lack of background knowledge, lack of enthusiasm about the course or problem, and lack of critical thinking surrounding CNSES. Additionally, the NRC (2012) Science and Engineering Practices serve to scaffold students towards expert-like behavior, and the components of an ill-structured problem frame the activity to encourage students to solve real-world problems like an expert. Together, these three interrelated concepts produce a model that may help to transition students from novice to expert-like behavior in the classroom and facilitate learning that will be more useful for life and the workplace.

We do not suggest that any of these components are more important than another; however, we suggest that by using all of these elements together, instructors and researchers may see the best results in the classroom. Future research into problem-solving in the geosciences in particular could focus on the least used components, which are the use of personal beliefs, expert performance and modeling, an interdisciplinary approach, and the use of unclear or unknown problem or goals. This review also highlighted a need for research into student cognition during ill-structured problem-solving in the geosciences, the effectiveness of problem-solving assessments, and the impact of specific scaffolds on learning during this process. Additionally, this model should be tested in classrooms to understand student transitions from novice to more expert-like behavior and the impact of the model upon instructor planning and course design.

In the future, we must ask ourselves, when does a problem become too ill-structured or well-structured for a particular course? Gill et al. (2014) suggests that "students should be given problems—at levels appropriate to their maturity—that require them to decide what evidence is relevant and to offer their own interpretations of what the evidence means," (p. 61) but how do we determine their "maturity"? The most common way to assess student maturity was to give a pre/post knowledge test to measure a baseline for student preexisting knowledge and provide a marker for how the activity impacted student knowledge; however, many times these pre/post knowledge surveys were not explicitly supported by citations or other expert backing, and we suggest in the future that all surveys, whether for knowledge, interest, or evaluation, should include some type of evidence to support the validity of the survey. Lev (2004) goes as far as suggesting that some students inability to problem-solve even at a small level may be a systematic failure: "But, how can a person with a B.S. in geology and no experience gain an appreciation for the complexity of even the smallest site investigation? The answer requires undergraduate geology departments to revise environmental geology curriculum so that the students going through our programs get the appropriate problem-solving skills they need to succeed" (p. 128). There is no easy answer to know if there is a need for a complete overhaul of the geoscience curriculum, but we hope that this model can provide a foundation for the design of research and instructional activities that involve problem-solving activities in the classroom.

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